The Impact of Weather Extreme Events on US Agriculture

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Overview

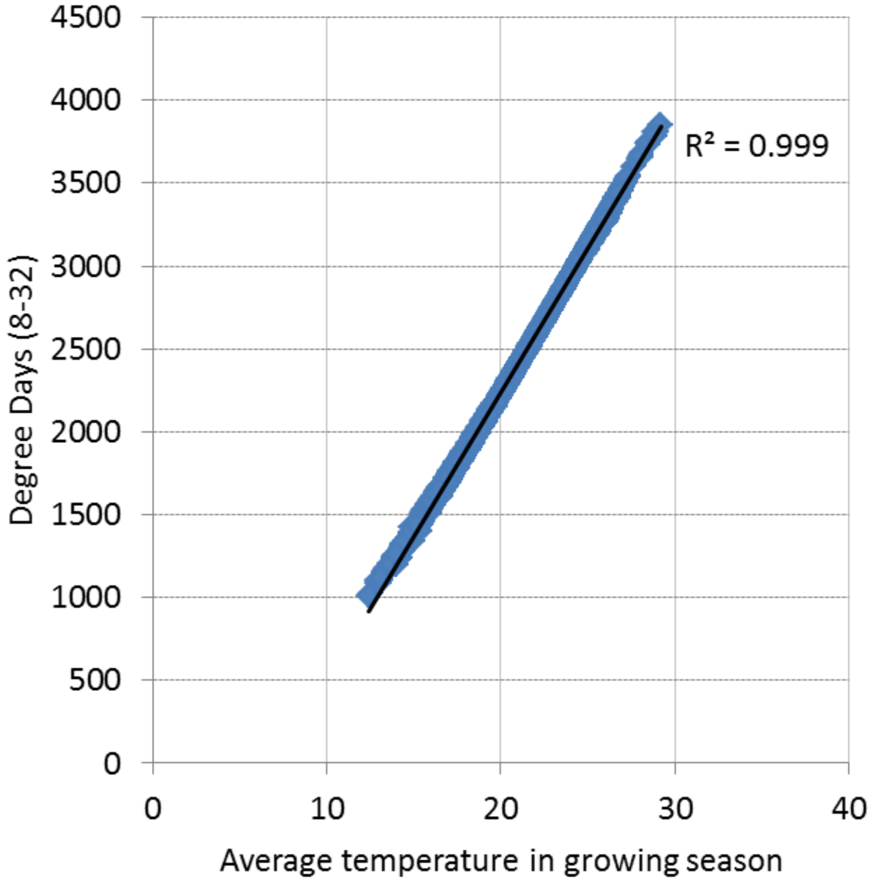
- Overview of recent work on climate and agriculture
- Context for today's presentation
- Extreme weather events and crop yields

Extreme vs Average Temperature

- Mendelsohn et al. (1994)
  - Seasonal quadratic specification of average temperature and precipitation

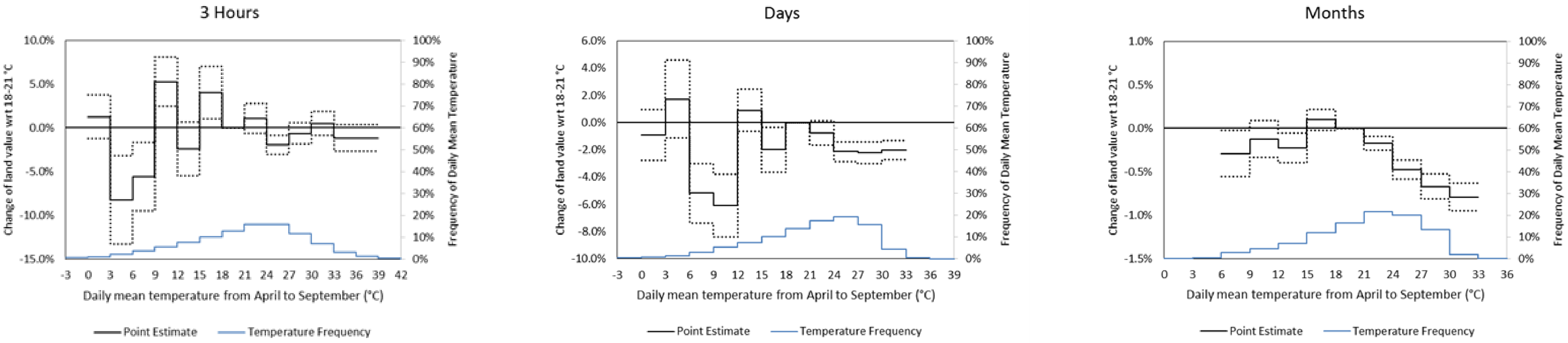
- Schlenker et al. (2006):
  - Degree days during the growing season
  - Threshold effect at 34 °C

- Massetti et al. (2016)
  - Agronomic literature does not use degree days to predict productivity
  - Degree days and average temperature are perfectly correlated
  - Model with four seasons outperforms the model with only the growing season
  - Days with T > 34 °C very rare, overestimated by Schlenker et al. (2006)
    - Threshold effect not significant and not robust
    - Very small effect



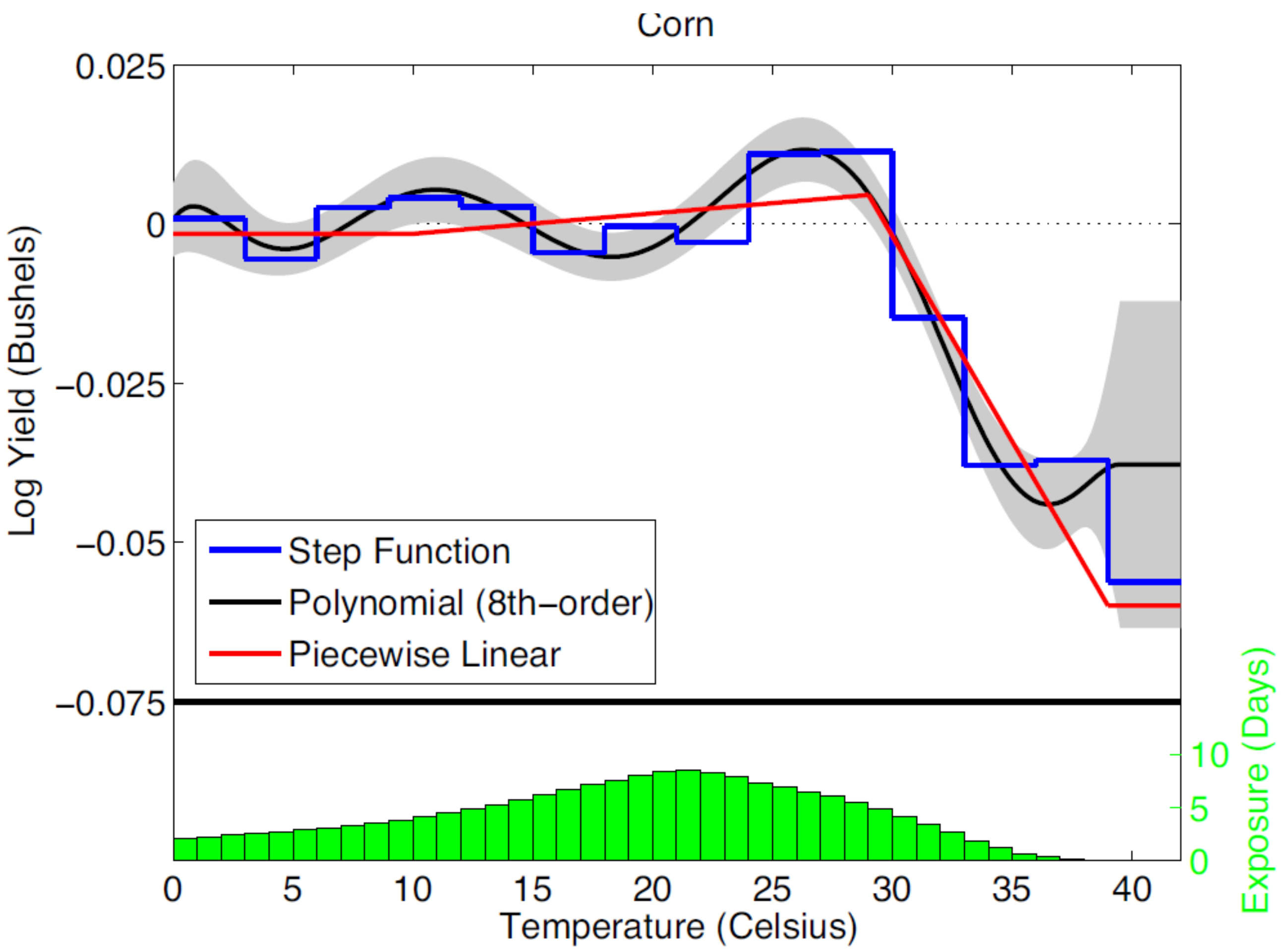
- There is no difference between degree days between 8-32°C and average seasonal temperature

In Search of Temperature Thresholds



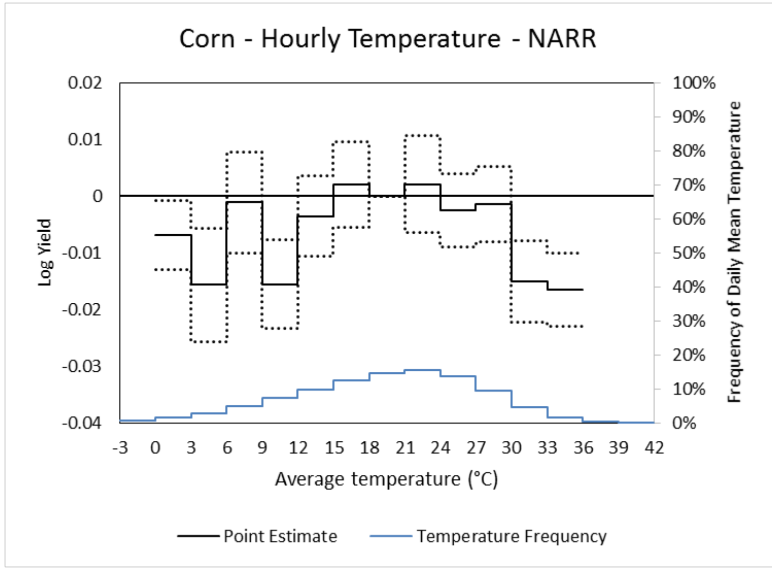
- Ricardian model with climatologies of temperature bins
- No temperature "thresholds"

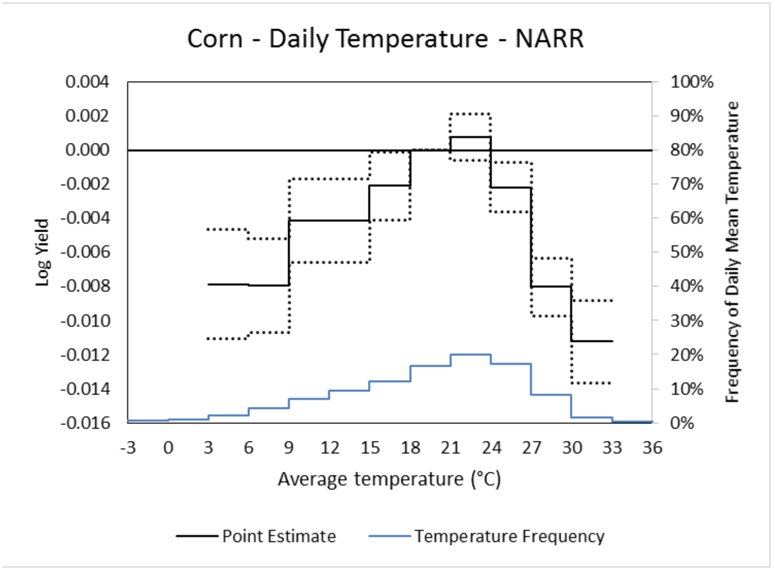
Massetti and Mendelsohn (2017a)

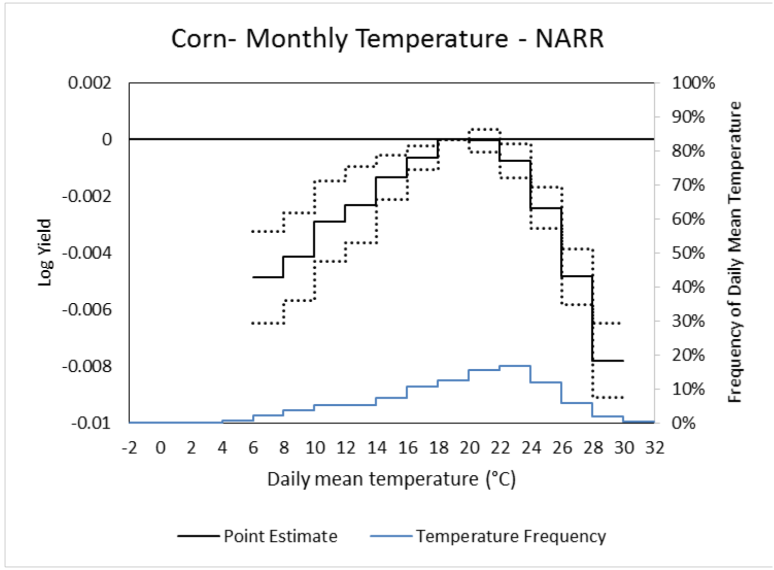


Corn
Log Yield (Bushels)
0.025
0
−0.025
−0.05
−0.075
Step Function
Polynomial (8th−order)
Piecewise Linear
10
5
0
Exposure (Days)
0
5
10
15
20
25
30
35
40
Temperature (Celsius)

Duration of Temperature Effects
Crop Yields Model







- Crop yield model as in Schlenker and Roberts (2009)
- Duration of temperature measurements matters

Massetti and Mendelsohn (2017b)

Measurement of Extreme Temperatures

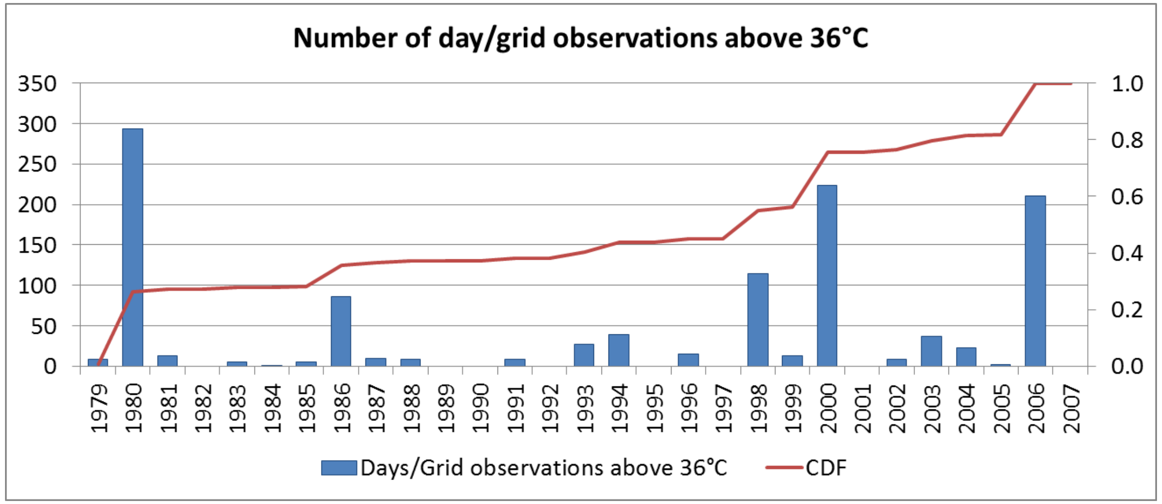
- Bins model are ill suited to estimate the effect of extreme temperatures

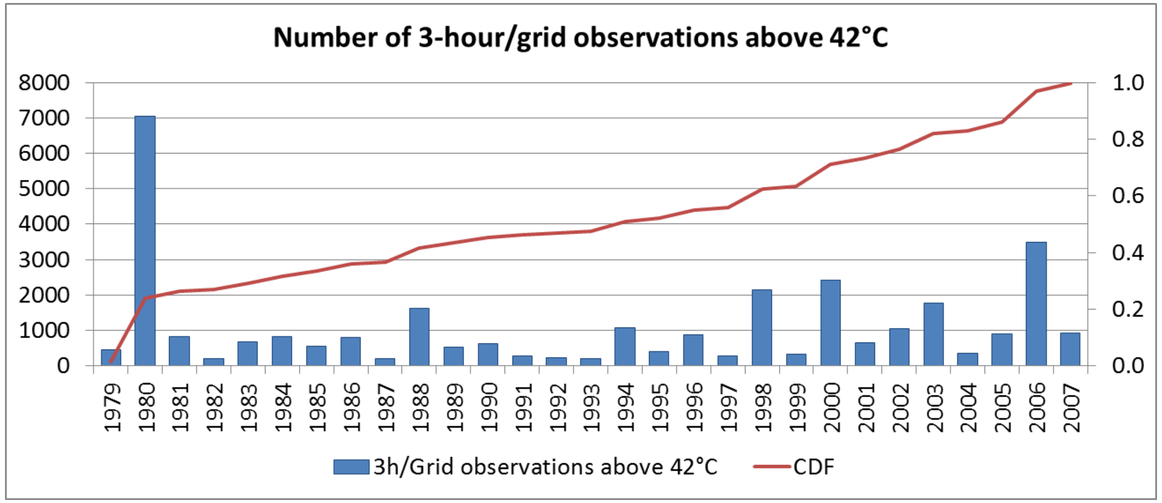
1. Duration matters, while bins typically assume the opposite

2. Extreme events are not uniformly distributed over space
   – The extreme bins are identified using a small subset of counties

3. Changes in extreme temperature bins may be correlated with other unobserved changes in climatic variables

Distribution of days above 36 °C



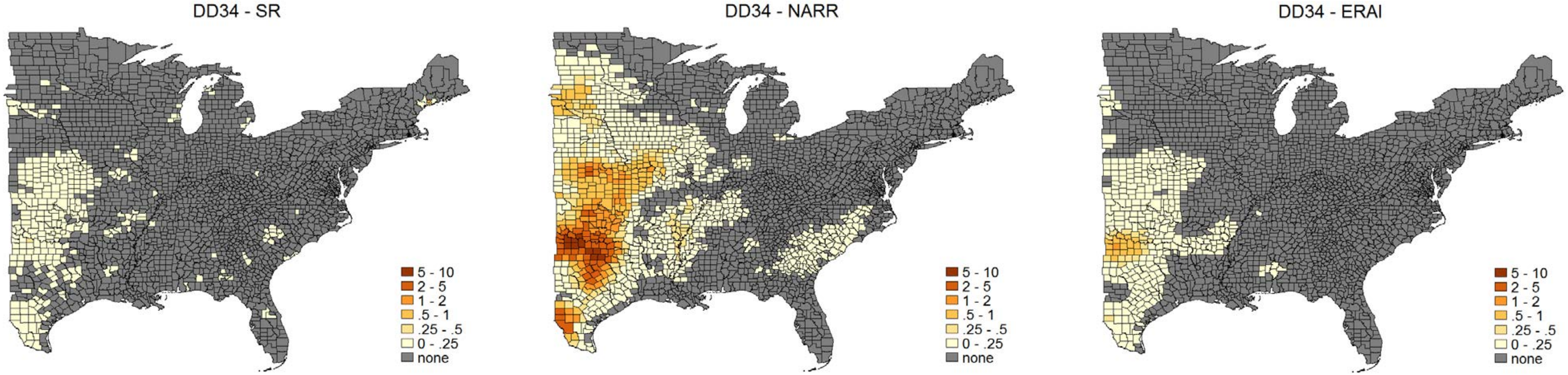


- 24,372 day/grid observations
- 194,976 3-hour/grid observations

- 1980, 1998, 2000, 2006 heat waves clearly distinguishable

1979-2007, East of the 100th meridian. Source our extrapolation using NARR data.

Extreme Temperatures



Days with mean temperature above 34 °C

Current Research on Weather Extremes

- Better measurement of
  - Extreme heat events
  - Droughts
  - Cold waves
  - Tornados and Hail
- Preliminary results in Ricardian model do not indicate a significant and consistent impact of weather extremes
- Focus on crop yields

Crop yield model

$$y_{i,t} = \alpha + \sum_{j=0,3,6,\ldots}^{J} \beta_j x_{i,j,t} + \gamma_1 P_{i,t} + \gamma_2 P_{i,t}^2 + \boldsymbol{\eta} X_{i,t} + \boldsymbol{\varphi} E_{i,t} + \eta_i + \epsilon_{i,t}$$

- Adapted from Schlenker and Roberts (2009)
  - $y_{i,t}$ is the log of yield per hectare in county *i* in year *t*
  - $x_{i,t,j}$ is the number of days with mean temperature within a 3 °C interval in year *t*
  - $P_{i,t}$ is the rainfall during April-September in year *t*
  - $X_{i,t}$ contains a state by year quadratic time trend
  - $E_{i,t}$ is a vector of extreme events observed in county *i* in time *t*
  - η_i is a county fixed effect
  - $\varepsilon_{i,t}$ is assumed to be a random component
  - Standard errors corrected for spatial and serial correlation

Weather and Climate Data

- Corn and soybeans yields in 1979-2007 from USDA
- Counties East of the 100th meridian in the US
- NARR 2 meter air temperature and precipitation from 1979
  - Temperature, precipitation
  - Heat waves
  - Variables calculated at grid-cell level and averaged at county level
- Robustness tests (in progress) with ERA-Interim and Schlenker and Roberts (2009) weather data
- NOAA climate divisions database
  - Drought
  - Area weighted average of climate divisions data
- NOAA storm events database
  - Hail and tornados
  - Number of events / 100 sq miles in each county

Heat and cold waves

- SREX IPCC report and NOAA:
  - A ***prolonged*** *period* of ***abnormally*** hot/cold weather
  - At least 3 consecutive days with mean temperature 2 standard deviations above/below climatological mean
  - Count events in each season at grid level, then average across all grid cells within a county
  - Robustness tests using 1.5 standard deviations and 5 consecutive days

Drought

- IPCC SREX report:

  A period of abnormally dry weather long enough to cause a serious hydrological imbalance. Drought is a relative term.

- Soil moisture (agricultural) drought
  - Imbalance between supply and demand of water
  - Palmer Drought Severity Index (PDSI)
- Meteorological drought
  - Lack of precipitation
  - Standardized Precipitation Index (SPI)
    - Number of standard deviations from average precipitation during X months before the month under consideration
    - 12 months periods in order not to capture seasonal effects
    - Used in robustness test

Hail and Tornados

- Hail has severe negative effects on crops
  - Localized but potentially destructive
  - Number of events/100 sq miles
  - Control for hail size in robustness tests

- Tornados have destructive impact but rare and spatial extent very limited
  - Separate minor and severe storms
  - Number of events/100 sq miles

Descriptive Statistics of County Area Weighted Averages

	Corn				Soybeans			
	Mean	St. Dev.	Min	Max	Mean	St. Dev.	Min	Max
Cold wave (count, Apr-Sep)	0.99	1.29	0	10.0	1.00	1.30	0	10.0
Heat wave (count, Apr-Sep)	0.12	0.37	0	4.00	0.12	0.39	0	4.00
Drought - PDSI Moderate (count, Apr-Sep)	0.66	0.68	0	2.0	0.65	0.68	0	2.0
Drought - PDSI Extreme (count, Apr-Sep)	0.04	0.10	0	0.50	0.03	0.10	0	0.50
Hail (count Apr-Sep / 100 sq. miles)	0.31	0.55	0	10.9	0.34	0.58	0	11.4
Tornado (Cat < 3) count, Apr-Sep / 100 sq. miles)	0.05	0.14	0	3.1	0.06	0.14	0	3.1
Tornado (Cat ≥ 3) (count, Apr-Sep / 100 sq. miles)	0.004	0.031	0	1.1	0.004	0.033	0	1.1

	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)				
Heat Wave (count, Apr-Sep)				
Drought - PDSI Moderate (count, Apr-Sep)				
Drought - PDSI Extreme (count, Apr-Sep)				
Hail (count/100 sq. miles, Apr-Sep)				
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

Notes: Notes: all coefficients have been multiplied by 100. A total of 55,030 county-year observations is used to estimate the corn yield model. 46,658 county-year observations are used to estimate the soybeans yield model. Unbalanced panels used for both corn and soybeans models. All standard errors corrected for spatial correlation.

	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)	-2.16***	-0.82*		
	[0.45]	[0.43]		
Heat Wave (count, Apr-Sep)	-3.48**	-2.11*		
	[1.44]	[1.18]		
Drought - PDSI Moderate (count, Apr-Sep)				
Drought - PDSI Extreme (count, Apr-Sep)				
Hail (count/100 sq. miles, Apr-Sep)				
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Drought - PDSI Moderate (count, Apr-Sep)	-3.23***	-1.86***		
	[0.72]	[0.64]		
Drought - PDSI Extreme (count, Apr-Sep)	-36.4***	-21.2***		
	[6.17]	[5.46]		
Hail (count/100 sq. miles, Apr-Sep)				
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

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	[6.17]	[5.46]		
Hail (count/100 sq. miles, Apr-Sep)	-0.91*	-0.85*		
	[0.54]	[0.52]		
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)				
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)				

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	[0.54]	[0.52]		
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)	-1.3	-1.74		
	[1.22]	[1.42]		
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)	-1.59	-4.7		
	[4.31]	[4.03]		

Notes: Notes: all coefficients have been multiplied by 100. A total of 55,030 county-year observations is used to estimate the corn yield model. 46,658 county-year observations are used to estimate the soybeans yield model. Unbalanced panels used for both corn and soybeans models. All standard errors corrected for spatial correlation.

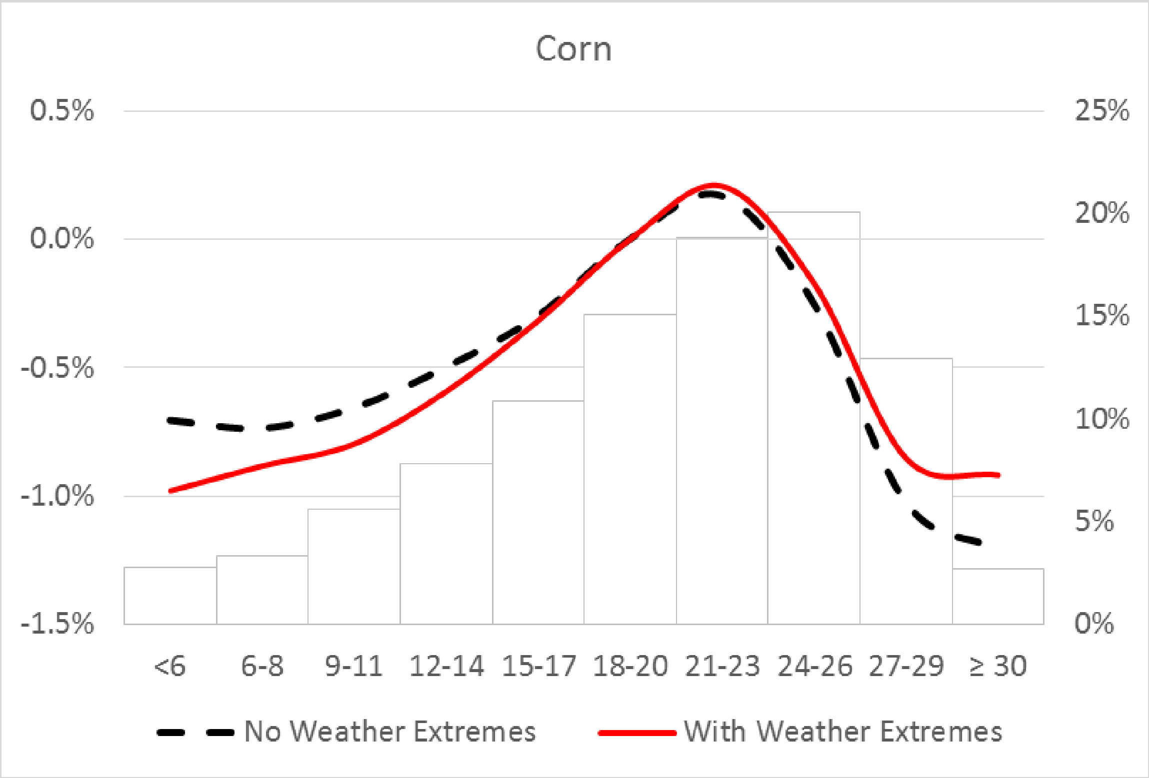
	Separately		All extreme events	
	Corn	Soybeans	Corn	Soybeans
Cold Wave (count, Apr-Sep)	-2.16***	-0.82*	-1.73***	-0.53
	[0.45]	[0.43]	[0.45]	[0.43]
Heat Wave (count, Apr-Sep)	-3.48**	-2.11*	-2.83**	-1.73
	[1.44]	[1.18]	[1.44]	[1.13]
Drought - PDSI Moderate (count, Apr-Sep)	-3.23***	-1.86***	-3.29***	-1.93***
	[0.72]	[0.64]	[0.71]	[0.64]
Drought - PDSI Extreme (count, Apr-Sep)	-36.4***	-21.2***	-29.8***	-18.3***
	[6.17]	[5.46]	[6.07]	[5.23]
Hail (count/100 sq. miles, Apr-Sep)	-0.91*	-0.85*	-0.88*	-0.75
	[0.54]	[0.52]	[0.71]	[0.64]
Tornado (Cat < 3) (count/100 sq. miles, Apr-Sep)	-1.3	-1.74	-1.41	-3.41***
	[1.22]	[1.42]	[1.13]	[1.02]
Tornado (Cat ≥ 3) (count/100 sq. miles, Apr-Sep)	-1.59	-4.7	-0.83	-4.1
	[4.31]	[4.03]	[4.22]	[3.96]

Notes: Notes: all coefficients have been multiplied by 100. A total of 55,030 county-year observations is used to estimate the corn yield model. 46,658 county-year observations are used to estimate the soybeans yield model. Unbalanced panels used for both corn and soybeans models. All standard errors corrected for spatial correlation.

Expected impacts of extreme events

Extreme Event	Corn	Soybeans
Cold Wave	-2.1%/year	-0.8%/year
Heat Wave	-0.4%/year	-0.2%/year
Drought	-3.3%/year	-1.9%/year
Hail	-0.3%/year	-0.3%/year
Tornado	-0.07%/year	-0.12%/year
TOTAL	**-6.2%/year**	**-3.3%/year**

Temperature-yield functions



- Similar changes for soybeans
- Similar pattern when using hourly temperature bins

Impact of 3 °C warming

	Corn	Soybeans
No extreme events		
With extreme events		

Impact of 3 °C warming

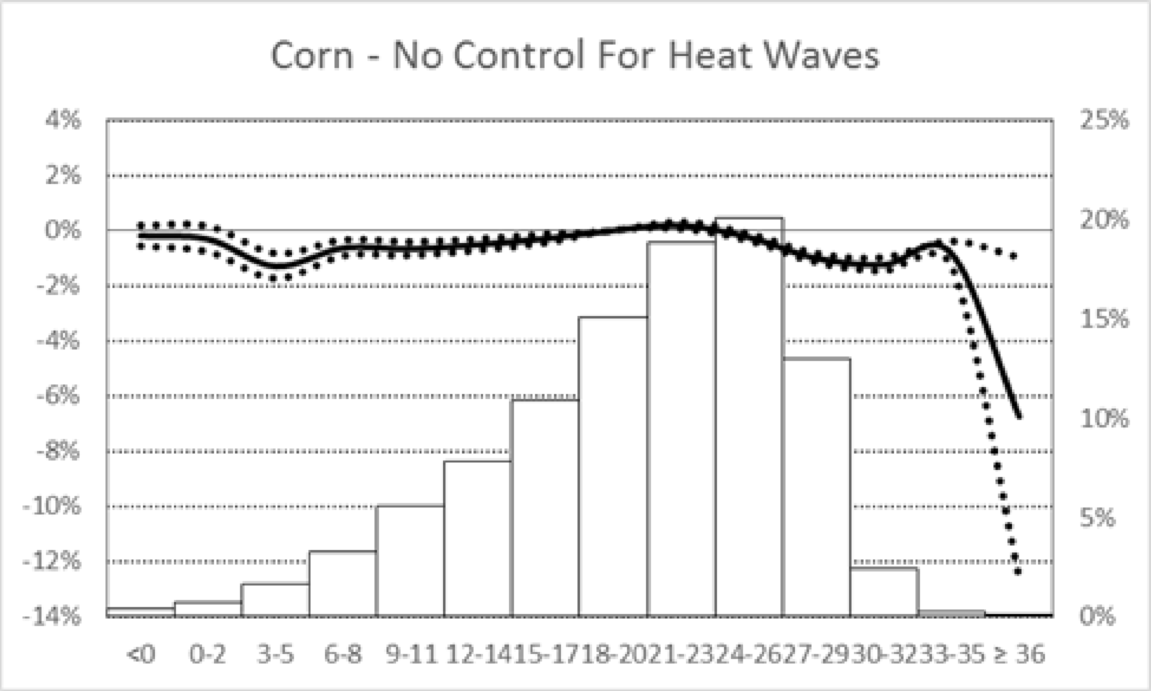
	Corn	Soybeans
No extreme events	-31.9% [-37.6% ; -26.1%]	-30.7% [-36.2% ; -25.2%]
With extreme events		

Impact of 3 °C warming

	Corn	Soybeans
No extreme events	-31.9% [-37.6% ; -26.1%]	-30.7% [-36.2% ; -25.2%]
With extreme events	-20.6% [-26.9% ; -14.2%]	-24.8% [-31.0% ; -18.7%]

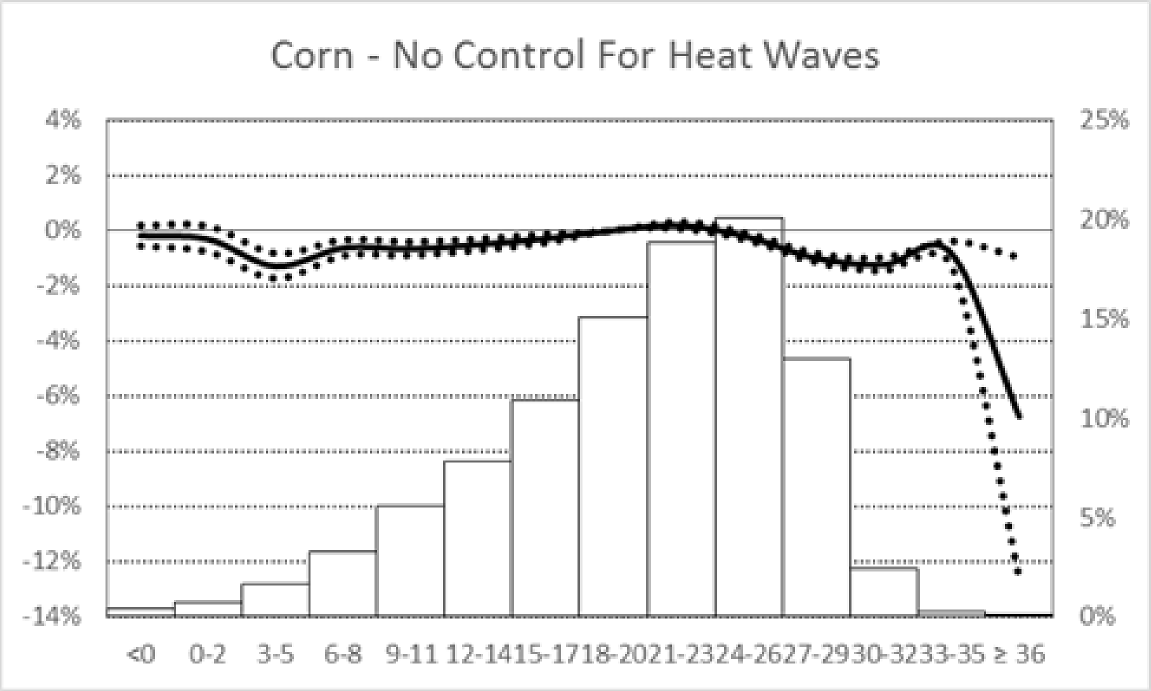
- The inclusion of extreme events reduces by 35% corn yield impacts and by 19% soybeans impacts from warming
- Of course, full impact estimates must consider change of extreme events

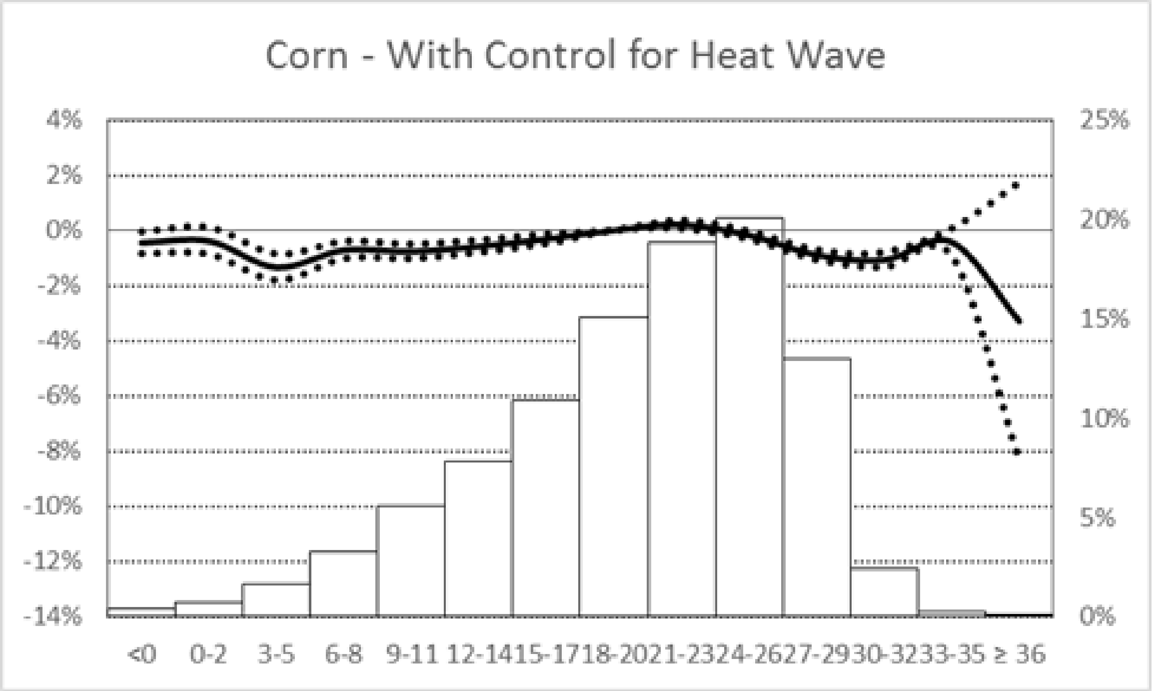
Extreme bins and heat waves



Notes: On the primary vertical axis impact on yields in percentage. The vertical axis measures the impact of substituting one day with mean temperature in a given bin with a day with mean temperature between 18 and 20 °C, the reference temperature level in our analysis. The dotted lines indicate the 95% confidence interval corrected for spatial correlation. The underlying histograms depict the mean daily temperature distributions over the counties and years included in the panel regression. The frequency of daily temperature observations is measured on the secondary axis. On the horizontal axis temperature measured in °C.

Extreme bins and heat waves





- Including a control for heat waves reduces the impact of the last bins

Notes: On the primary vertical axis impact on yields in percentage. The vertical axis measures the impact of substituting one day with mean temperature in a given bin with a day with mean temperature between 18 and 20 °C, the reference temperature level in our analysis. The dotted lines indicate the 95% confidence interval corrected for spatial correlation. The underlying histograms depict the mean daily temperature distributions over the counties and years included in the panel regression. The frequency of daily temperature observations is measured on the secondary axis. On the horizontal axis temperature measured in °C.

Duration and severity of extreme temperature

	> 3 days 2 stdev	> 3 days 1.5 stdev	> 5 days 2 stdev	> 5 days 1.5 stdev
CORN				
cold wave	-2.16***	-1.27***	-2.76***	-1.36***
	[0.45]	[0.32]	[0.52]	[0.37]
heat wave	-3.48**	-2.1***	-7.72	-5.48***
	[1.44]	[0.64]	[5.05]	[1.5]
SOYBEANS				
cold wave	-0.82*	-0.63**	-0.98**	-0.55
	[0.43]	[0.31]	[0.49]	[0.35]
heat wave	-2.11*	0.36	-3.28	-3.04**
	[1.18]	[0.57]	[3.11]	[1.35]

- Evidence that duration matters

Duration and severity of extreme temperature

	> 3 days 2 stdev	> 3 days 1.5 stdev	> 5 days 2 stdev	> 5 days 1.5 stdev	All temperature bins
CORN					
cold wave	-2.16***	-1.27***	-2.76***	-1.36***	-0.55**
	[0.45]	[0.32]	[0.52]	[0.37]	[0.23]
heat wave	-3.48**	-2.1***	-7.72	-5.48***	-5.83**
	[1.44]	[0.64]	[5.05]	[1.5]	[2.84]
SOYBEANS					
cold wave	-0.82*	-0.63**	-0.98**	-0.55	-0.7
	[0.43]	[0.31]	[0.49]	[0.35]	[1.15]
heat wave	-2.11*	0.36	-3.28	-3.04**	-2.6**
	[1.18]	[0.57]	[3.11]	[1.35]	[1.16]

- Evidence that duration matters

Duration and severity of extreme temperature

	> 3 days 2 stdev	> 3 days 1.5 stdev	> 5 days 2 stdev	> 5 days 1.5 stdev	All temperature bins	Average Temperature
CORN						
cold wave	-2.16***	-1.27***	-2.76***	-1.36***	-0.55**	-3.88***
	[0.45]	[0.32]	[0.52]	[0.37]	[0.23]	[0.56]
heat wave	-3.48**	-2.1***	-7.72	-5.48***	-5.83**	-5.58***
	[1.44]	[0.64]	[5.05]	[1.5]	[2.84]	[1.69]
SOYBEANS						
cold wave	-0.82*	-0.63**	-0.98**	-0.55	-0.7	-2.56***
	[0.43]	[0.31]	[0.49]	[0.35]	[1.15]	[0.47]
heat wave	-2.11*	0.36	-3.28	-3.04**	-2.6**	-4.25***
	[1.18]	[0.57]	[3.11]	[1.35]	[1.16]	[1.24]

- Evidence that duration matters

Standardized Precipitation Index

	CORN	SOYBEANS
Drought - SPI 12 months SPI < -2.5 (months, during Apr-Sep)	-43.24**	-36.3**
	[21.35]	[14.92]
Drought - SPI 12 months -2.5 ≤ SPI < 1.0 (months, during Apr-Sep)	-12.91*	-2.04
	[7.67]	[7.86]
Drought - SPI 12 months -1.0 ≤ SPI < 0 (months, during Apr-Sep)	-2.45	-3.05
	[2.5]	[2.43]
Wet spells - SPI 12 months SPI > 2.5 (months, during Apr-Sep)	-15.77	-5.64
	[11.21]	[10.35]
Wet spells - SPI 12 months 1.0 < SPI ≤ 2.5 (months, during Apr-Sep)	1.15	5.87
	[2.5]	[2.43]
Wet spells - SPI 12 months 0 < SPI ≤ 1.0 (months, during Apr-Sep)	-7.59***	-4**
	[1.9]	[1.61]

Notes: The SPI index measures the number of months during the growing season during which the average precipitation during the previous 12 months is 0 to 1, 1 to 2.5 or more than 2.5 standard deviations from the long-term mean during the same period.

Conclusions

- Climatic events are complex phenomena that must be carefully modeled
- Extreme events reduce corn yields by 6% and soybean yields by 3% per year
  - Severe droughts are very harmful but rare
  - Cold waves more harmful than heat waves
- Interaction between extreme events remains to be explored
- Additional work should include a much richer specification of atmospheric variables

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